Defending the Nation's Harbors: A Model-Based Response to Nuclear Terrorism

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October 5, 2010

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Defending the Nation's Harbors: A Model-Based Response to Nuclear Terrorism

A novel sequential Bayesian approach provides a rapid and reliable technique to detect and identify illicit radioactive materials thwarting terrorism

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Whether a Coast Guard patrol boat is interdicting and searching a vessel in a harbor for illicit radioactive materials or cargo containers are being off-loaded from a ship or a container truck is passing through portal monitor, the need to investigate techniques that can provide for more sensitive detection of terrorist threats demand that meaningful approaches be developed to solve many critical security problems for the protection of populations and valuable national resources. The detection of radioactive contraband is a critical problem in maintaining national security for any country. There exists a need for a rapid and reliable radiation detection system capable of determining the presence of nuclear threats with high confidence while minimizing false alarms in this era of global terrorism.

Photon emissions from threat materials challenge both detection and measurement technologies. This problem becomes especially important when ships are intercepted by U.S. Coast Guard harbor patrols searching for contraband. The development of a sequential model-based processor that captures both the underlying transport physics of photons or equivalently gamma-ray emissions including downscattering (Compton) and the measurement of photon energies offers a physics-based approach to attack this challenging problem. The inclusion of a basic radionuclide representation of absorbed/scattered photons at a given energy along with interarrival times can be used to extract the physics information available from the noisy measurements of portable radiation detection systems. This representation can be incorporated into a model-based structure that can be used to develop an effective sequential detection technique.

Approach

Researchers at the Lawrence Livermore National Laboratory (Livermore, CA) have uncovered a novel and revolutionary approach to solving this long-time problem. Based on fundamental transport physics, a unique solution to this detection problem incorporating physics-based signal processing models into a processor capable of providing rapid and reliable radionuclide (RN) detection is developed. The result is a statistical radiation detection (software) system or SRaDS, a completely novel software system capable of rapidly and confidently identifying *any* set of targeted radionuclides in a wide range of scenarios such as portal systems, first responder activities, verification activities, harbor and cargo inspections. It operates in a multitude of

environments and scenarios including uncertain low-count radiation measurement data. It represents the next generation of radiation detection system incorporating transport physics and sequential detection methods empowered by modern Bayesian signal processing algorithms capable of making a more rapid decision with higher confidence possessing its inherent ability to quantify performance. SRaDS automatically rejects extraneous and non-targeted photons during the measurement process increasing its performance capability significantly by reducing false alarms. It provides a faster, more reliable way to detect radioactive contraband in a variety of critical screening applications. It satisfies the critical need to develop a fast and reliable *automated* technique to detect and identify radioactive threat materials from uncertain radionuclide measurements especially when measurement time is short and the demand for confidence is high.

SRaDS utilizes the statistical nature of radiation transport as well as modern signal processing techniques to implement a physics-based, *sequential* statistical processor. Conceptually, a generic sequential detection technique is based on processing each photon arrival individually along with the corresponding decision function and thresholds. At each arrival the decision function is *sequentially updated* and compared to thresholds to perform the detection --- "photon-by-photon". The thresholds are selected from a receiver operating characteristic (ROC) curve (detection versus false-alarm probability) for each individual radionuclide decision function. An operating point is selected from the ROC corresponding to specific desired probabilities thereby specifying the thresholds for each radionuclide targeted.

How it works

Instead of accumulating a pulse-height spectrum (PHS) or energy histogram as is traditionally done in current systems, each photon is processed individually upon arrival and then discarded. After the single photon is acquired, the energy and arrival time measurements are passed to the energy/rate discriminators to determine the photon's status (accept or reject). If acceptable, the parameter estimates are sequentially updated and provided as input to update the decision function for detection and eventual identification. If rejected, the photon is discarded in contrast to PHS systems. Detection is declared when such a decision is *statistically* justified using estimated detection and false alarm probabilities specified by a ROC curve obtained during calibration. The result is a system that has improved detection performance with high reliability and short decision times.

The key issue in **SRadS** is developing reasonable statistical models of both emission and measurement processes that can effectively be used in the Bayesian framework. These stochastic models of the physical process must incorporate the loss of information resulting from the absorption of energy between an ideal source and the detector. The underlying probability distributions describe the physics of the radiation transport between the source and the detector. This approach differs from spectroscopy in that it models the source radionuclides by decomposing them uniquely as a superposition (union) of monoenergetic (single energy) sources that are then smeared, scattered and distorted as they are transported through the usual path to the detector for measurement and counting. The measured data consists of a low energy count, random, impulse-like, time series measurements (energy vs time) in the form of an event mode sequence (EMS) obtained from pulse shaping circuitry available in all commercial radiation detectors. The

main focus of this effort was to demonstrate not only how to use energy/rate measurements as well as both absorbed (photoelectron) and downscattered photon information in a sequential processor for detection.

How it is implemented

The pragmatic implementation is accomplished in various stages: (1) photon discrimination; (2) energy, rate and emission probability parameter estimation; (3) decision function calculation; and (4) threshold comparison. Operations are performed in the three distinct phases: discrimination, estimation and detection with confidence interval estimators performing the simple channel discrimination tasks, sophisticated *model-based* parameter algorithms (nonlinear Kalman and Bayesian particle filters) performing the estimation, updating the sequential decision function and performing the threshold detection---"photon-by-photon."

Discrimination is performed with the "true" parameters obtained from the tables of radionuclides (energy, rate (interarrival) and emission probability) or a radiation transport (signal processing) model for the downscatter implementation. From this information, the confidence intervals are constructed to decide if the photon arrival is valid for one of the targeted radionuclide components. If so, parameter estimation is performed using a linear Kalman filter for energy (Gaussian model) and particle filter for rate/interarrival (exponential model). The emission probability is calculated by sequentially updating valid counts in the channel. With these parameter estimates available, the decision function is sequentially updated and compared to the thresholds. Finally, in order to calculate the required thresholds for the detector, we must generate an ROC curve from simulation or high fidelity calibration data and pick an operating point specified by the desired detection and false alarm probabilities.

Thus, each unique energy/arrival component of the target radionuclide is processed individually in a separate channel resulting in the parallel/distributed processor structure. If the photon (photoelectron only) does not pass the discrimination test, then it is sent to the downscatter (Compton) processor or rejected. If accepted, it is further processed to improve the estimates of energy, rate and emission probability before being used to update the decision function.

Following the path of a photon through the distributed processor, SRaDS: (1) *discriminates* its energy identifying one of the parallel channels; (2) *discriminates* the corresponding detection rate (interarrival) parameter for that particular channel; (3) *enhances* the channel energy, rate and emission probability parameters; (4) *updates* the corresponding decision function; and (5) *detects/identifies* the target radionuclide by thresholding the decision function.

Results

A proof-of-concept experiment was developed to assess the feasibility of the sequential Bayesian processor. Three source radionuclides cobalt (^{60}Co), cesium (^{137}Cs), barium (^{133}Ba) were targeted in a laboratory environment contaminated with background and extraneous sources. The equipment used in the experiment consisting of sources, measurement instruments including commercial germanium and sodium-iodide detectors. The sources were positioned such that they were centered on a direct line with the detector face at a distance of 100 centimeters for 1000

seconds. Each target source and background was individually counted with the results combined to generate the controlled feasibility data set.

Results of this photon-by-photon processor with downscatter are quite good. By observing the composite pulse-height spectrum (not used in the processor) along with measured photon energies (arrivals), the discriminated absorbed (photoelectrons) and downscatter photons are easily detected based on their energy/rate parameters. The corresponding decision function for each of the targeted radionuclides is sequentially updated after parameter estimation until one of the thresholds (target/non-target) is crossed declaring a threat or non-threat. Based on an operating point of (98%, 2%) detection and false alarm probability, each of the targets was detected and classified in less than 6 seconds.

The performance of the processor was further substantiated by generating an ensemble of 100 members from the controlled experimental data and comparing it to the GAMMANAL (standard) software solution where SRaDS detection rate of 98% easily exceeded that of 47% for GAMMANAL both at essentially 0% false alarm rate. These results are outstanding and demonstrate the potential capability of the sequential Bayesian model-based approach for solving a variety of radiation detection problems.

SRaDS has also been implemented using sodium-iodide radiation detectors with lower resolution than the high purity germanium (HPGe) detectors used initially. The results are also quite good almost matching those performance metrics of HPGe with detection probabilities of 98% with higher false alarm probabilities of 12%. Teaming with ICx Technologies Inc. (Arlington, VA), a well-known, portable radiation detection system manufacturer, an award for one of the top 100 inventions of 2010 (R&D100) was received for this system.

Summary

This article has discussed the development of a novel automated radiation detection software system to solve a long-time problem of detecting the presence of illicit radioactive materials. SRaDS provides a more timely decision (sequential detection) with higher confidence (thresholding) and quantifiable performance capability (ROC curves) offering a rapid and reliable solution to the counterterrorism and nonproliferation problems.

Acknowledgments

Biography

James V Candy is the Chief Scientist for Engineering at the Lawrence Livermore National Laboratory and an adjunct Professor at the University of California, Santa Barbara. He is a Fellow of the Acoustical Society of America and of the IEEE. He was awarded the IEEE Distinguished Technical Achievement award and the ASA

Helmholtz-Rayleigh Interdisciplinary Silver Medal for contributions to model-based signal processing in acoustics and underwater sound. He has published four textbooks in signal processing.

FIGURE CAPTIONS

Figure 1. Radiation Detection Problem: Cargo containers aboard ship, small craft and portal inspections for illicit radioactive materials. SRaDS detection system providing detection and RN identification.

Figure 2. SRaDS design: discrimination of absorbed and downscattered (Compton) photons, rejection of background, and estimation of targeted radionuclide parameters for sequential decision function update and RN identification.
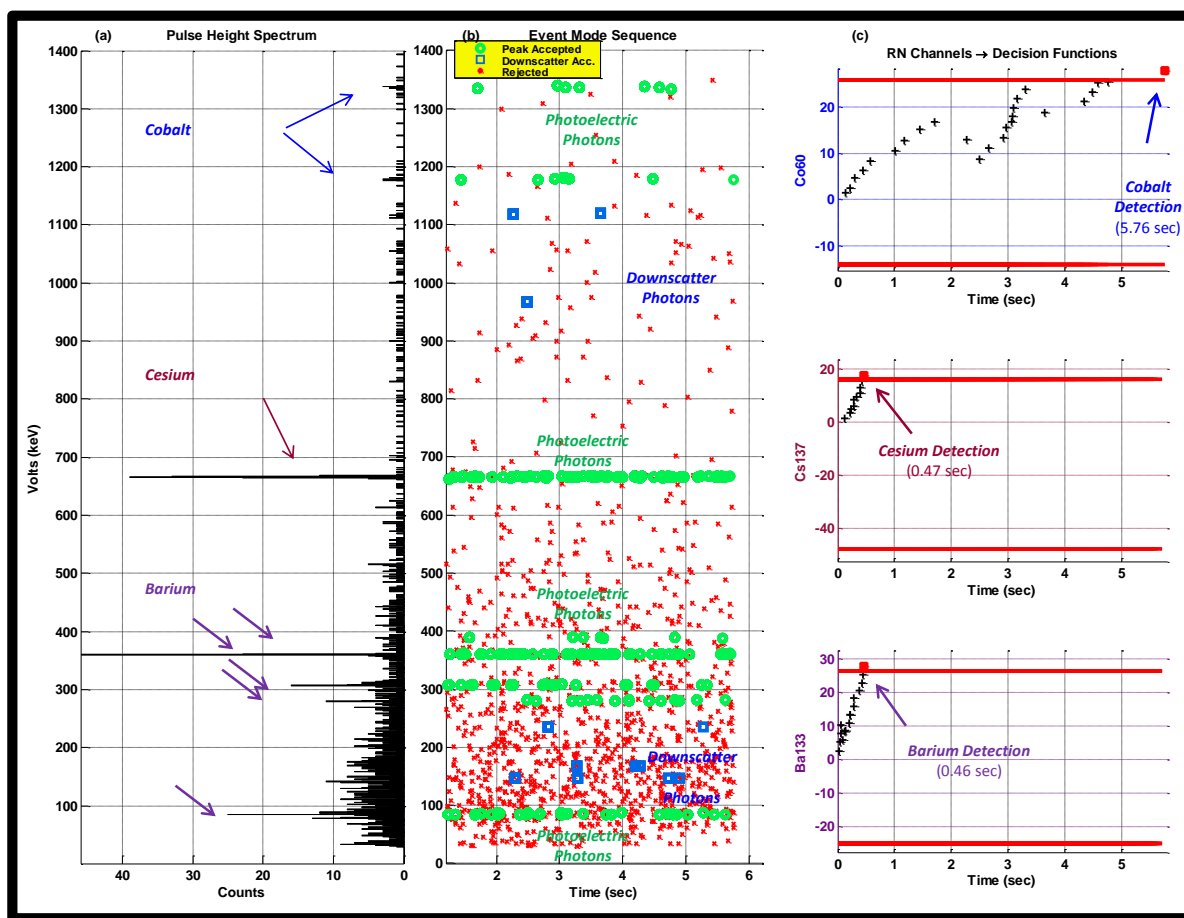

Figure 3. SRaDS results: (a) PHS. (b) Arrivals (red); discrimination: photoelectrons (green), downscatter (blue). (c) Decision functions: ^{60}Co (5.76 seconds), ^{137}Cs (0.47 seconds) and ^{133}Ba (0.46 seconds).

Candy_OctNov_FIG1.jpg
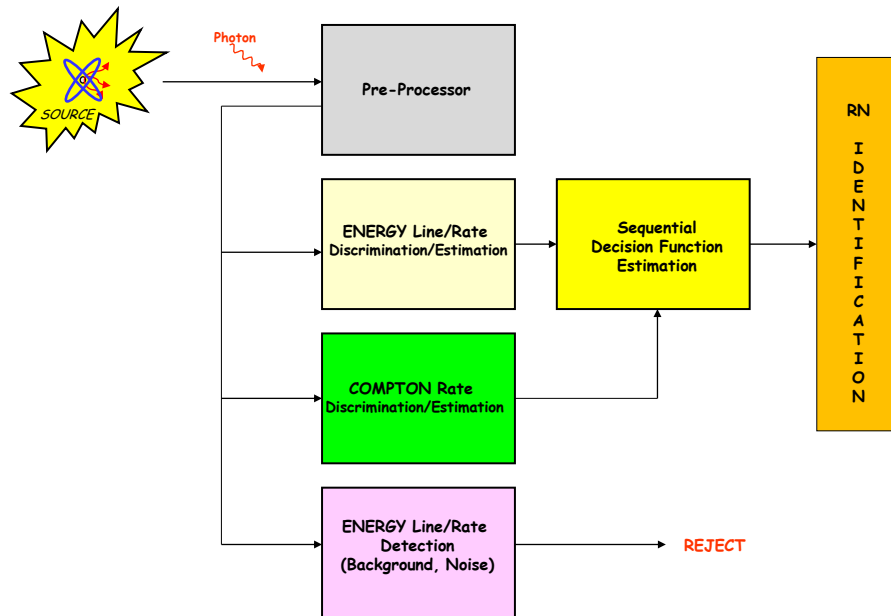
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